Geometry Modeling and Grid Generation for Design and Optimization

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Outline

- o Motivations
- o CAD
- o Grid Generation
- o Design & Optimization
- o Summary

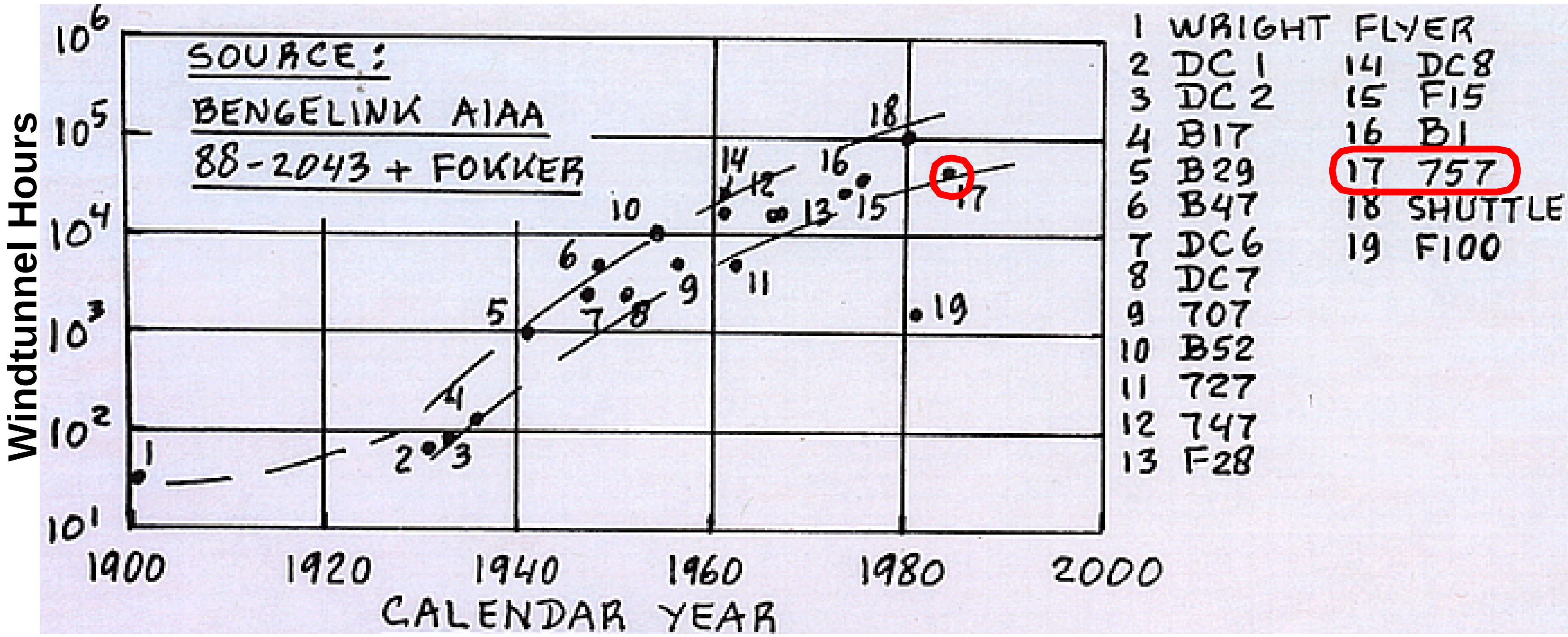
Overview

Geometry modeling and grid generation are an enabling technology for traditional design processes of today and even more so for the revolutionary integrated multidisciplinary processes of tomorrow.

The geometry modeling and grid generation tools must have the following characteristics:

- be automated,
- provide consistent geometry across all disciplines,
- be parametric,
- provide sensitivity derivatives.

Motivations



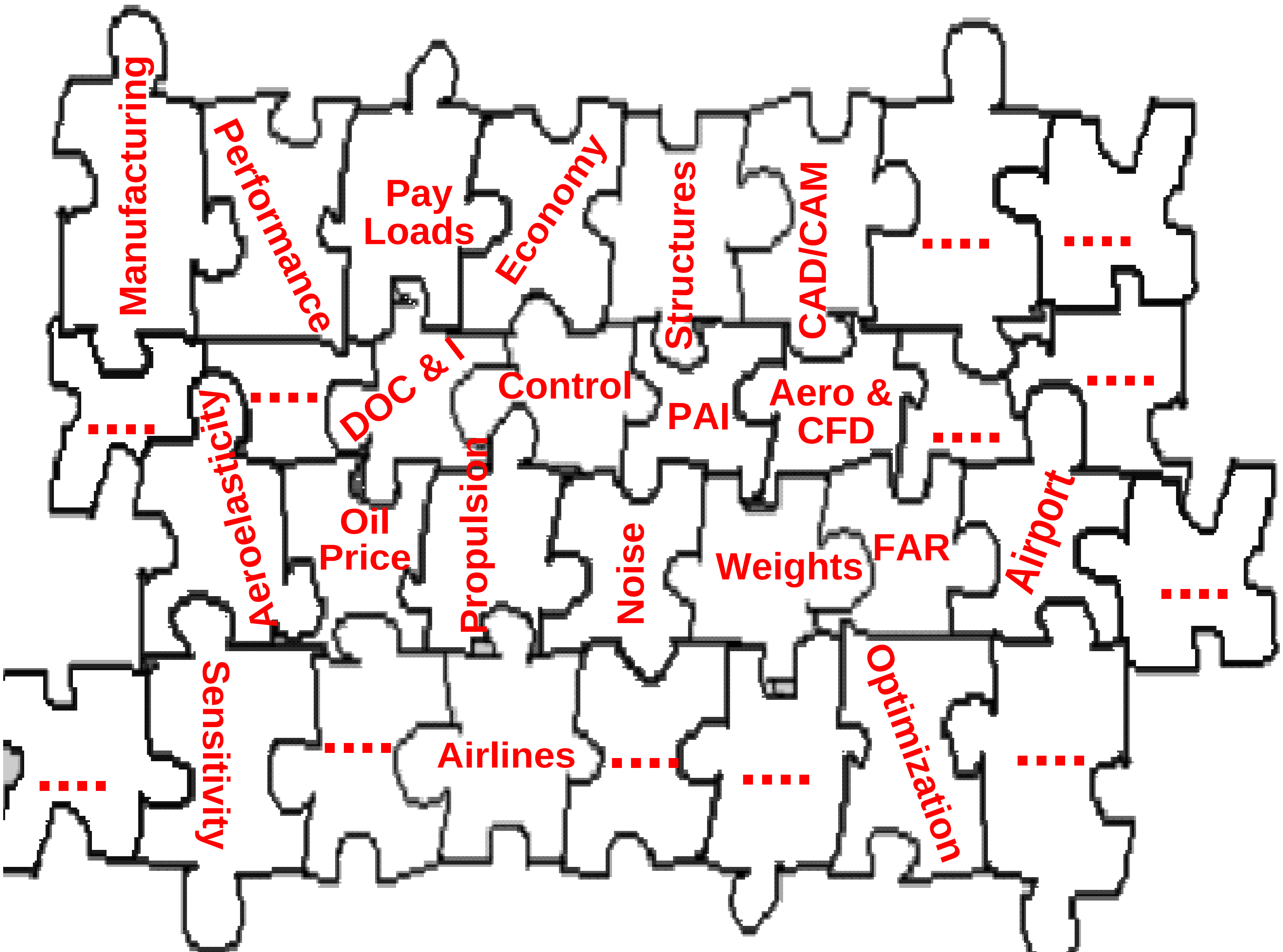
Windtunnel Hours Required for Typical Airplane Design
(Airplane Design, Jan Roskam 1990)

1975 Prediction

"To displace wind tunnels as the principal source of flow simulations for aircraft design computers must reach about 10^4 times the speed of the Illiac IV." Dean Chapman 1975

"The NAS Facility's CRAY C90 currently delivers 4−5 gigaflops of sustained performance on the production workload.", NAS WWW page (http://www−sci.nas.nasa.gov/Pubs/NASnews/97/03/cluster.html#997139)

Airplane Design Puzzle



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Are geometry modeling and grid generation tools ready to be integrated into a Multidisciplinary Design and Optimization (MDO)* environment for complex models?

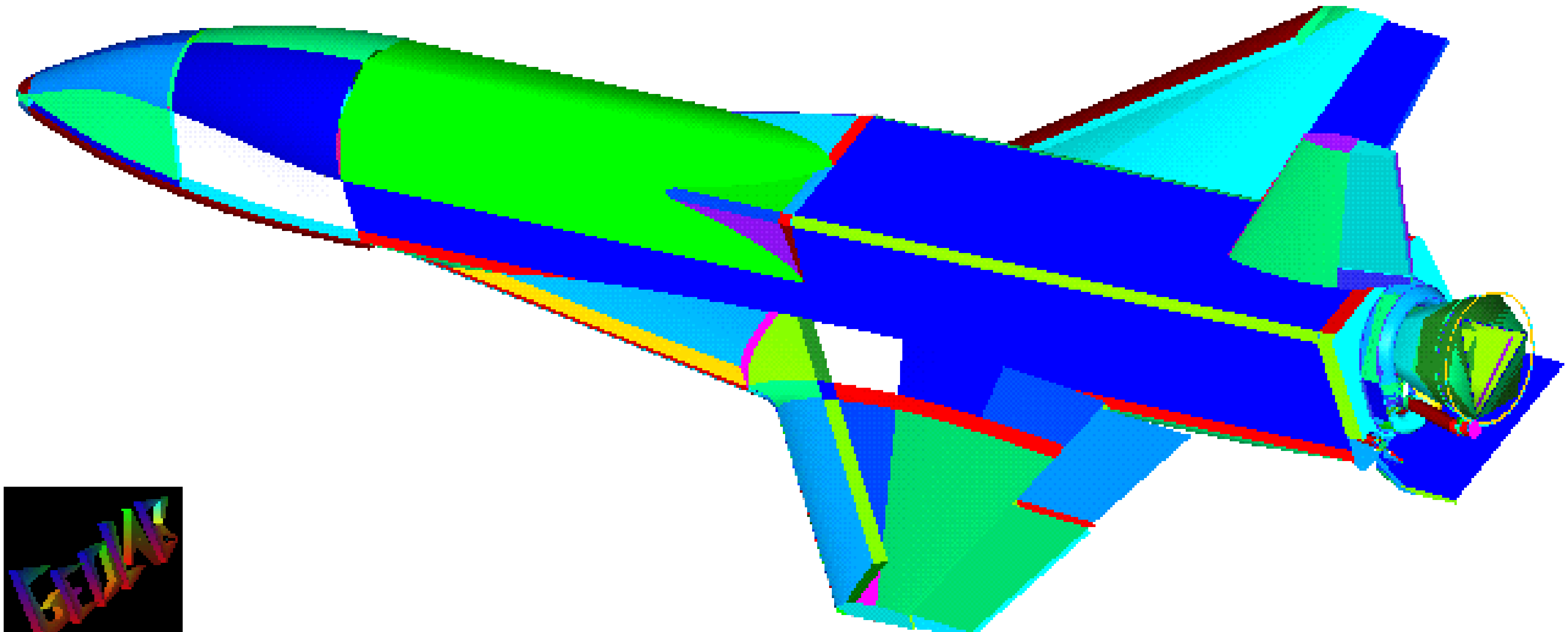
*** MDO exploits the synergism of mutually interacting phenomena**

Geometry and Grid Sensitivity

Gradient based optimization requires sensitivity data. e. g., $\dfrac{\delta \mathrm{Stress}}{\delta t}$

	CFD CSM		Grid Generation		Geometry Modeler (CAD)
$\dfrac{\delta Cd}{\delta t} =$	$\dfrac{\delta Cd}{\delta \mathrm{Grid}}$	x	$\dfrac{\delta \mathrm{Grid}}{\delta \mathrm{Geometry}}$	x	$\dfrac{\delta \mathrm{Geometry}}{\delta t}$
$\dfrac{\delta \mathrm{Stress}}{\delta t} =$	$\dfrac{\delta \mathrm{Stress}}{\delta \mathrm{Grid}}$	x	$\dfrac{\delta \mathrm{Grid}}{\delta \mathrm{Geometry}}$	x	$\dfrac{\delta \mathrm{Geometry}}{\delta t}$

Complex Geometry



X34 Model (23, 555 Curves & Surfaces)

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What do we need?

- o CAD
  - − Design oriented CAD systems
  - − Consistent CAD model for all disciplines

- o Grid Generation
  - − Automatic/accurate tools to transfer geometry from CAD to grid generators
  - − Fully automatic (push button) grid generators
  - − Tools to handle complex models
  - − Environment for non−expert users which allows <u>short design cycle time</u>*

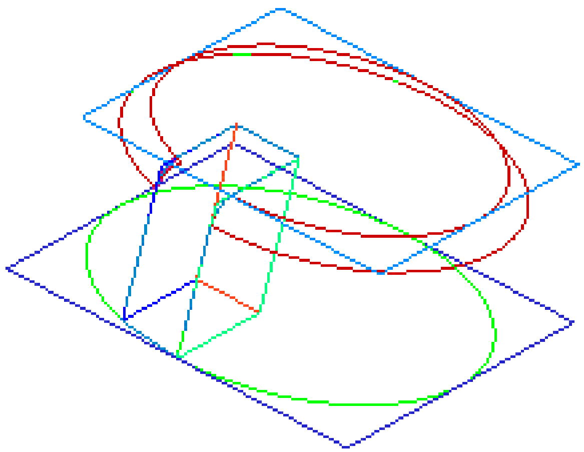
- o Design & Optimization
  - − Parametric models
  - − Tools to calculate geometry, grid and their sensitivities
  - − Tools to handle multidisciplinary interactions

*"A better rule of thumb is to assume that cost will be proportional to the calendar time required to do the job," Paul Rubbert, 1994.

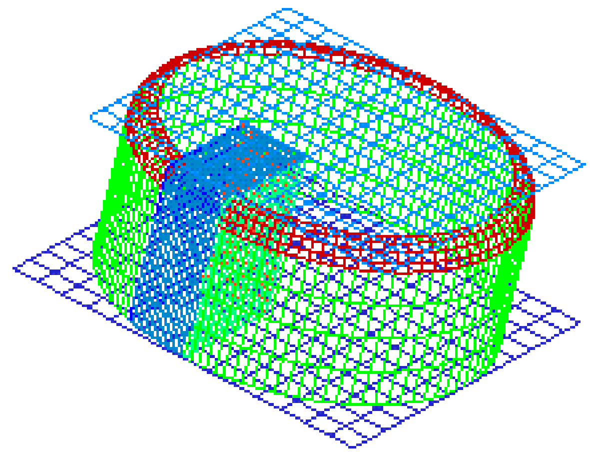
Status of CAD

- A complex geometry is difficult to model and it requires a CAD specialist.
- NonUniform Rational B−Splines (NURBS) can represent commonly used mathematical representations for curves and surfaces.
- Solid modeling can automate the creation of geometry topology.
- Feature/parametric CAD can parametrize complex models.

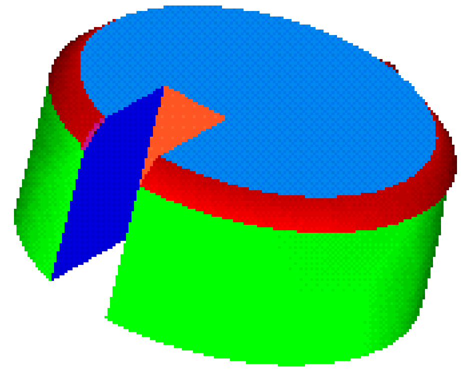
Solid Modeling (SM)



Wireframe Model (early 80s)



Surface Model (late 80s)

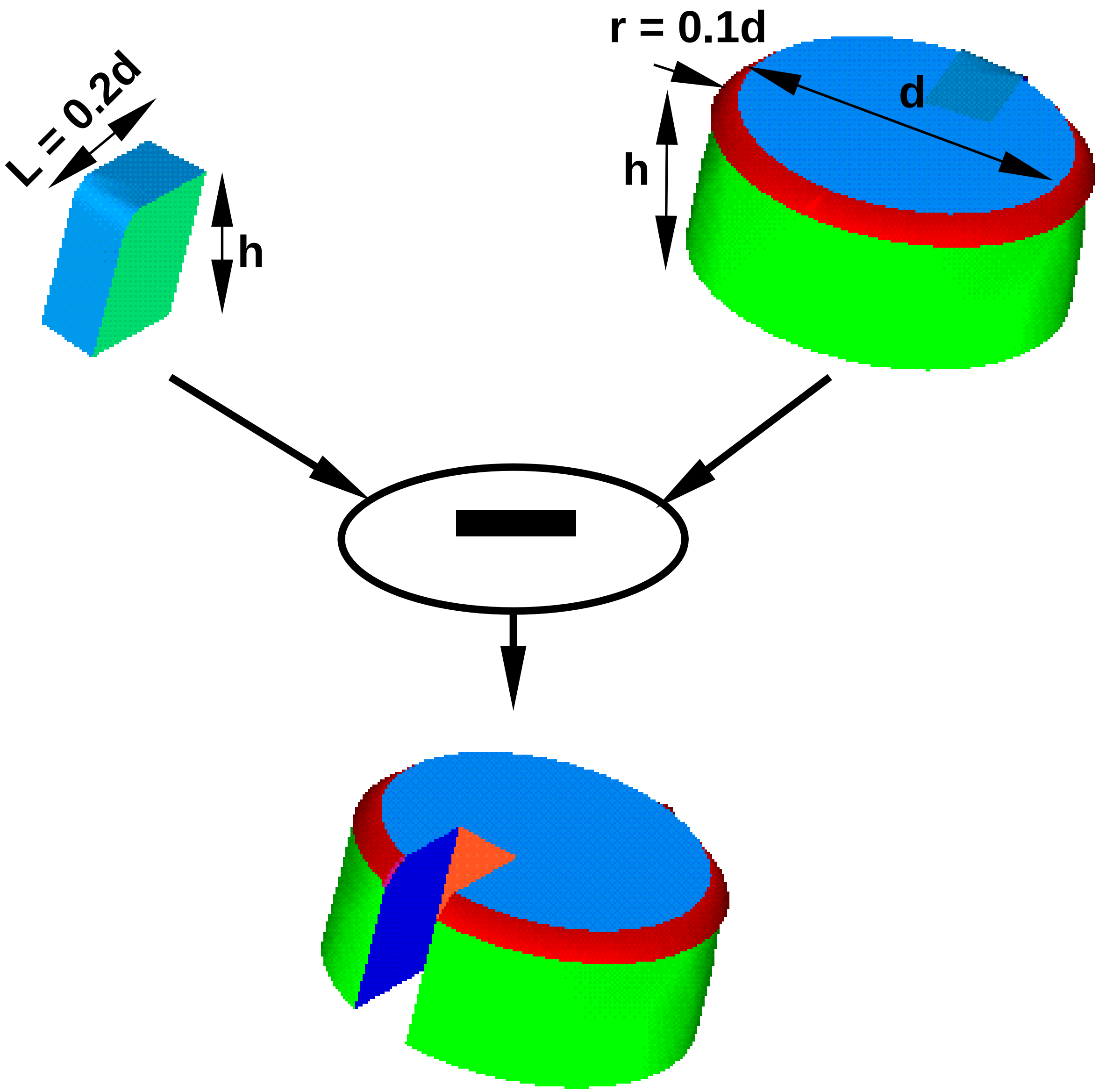


Manifold Solid B−Rep Model (early 90s)

Solid Modeling

- Creates a complete mathematical representation of solid object (B−Rep).
- Automates the process of creating surface geometry and topology.
- Avoids design errors.
- Can be converted to a physical model (e.g. stereolithography)
- Can be used in FEA, CFD, boundary−elements, ...
- Lacks the design intent.
- Design changes are time consuming.
- Finished design is featureless.
- Design process is bottom−up.
- Models may not be complete due to lack of a consistent tolerance.
- Is not mature for data exchange.

Feature−Based CAD



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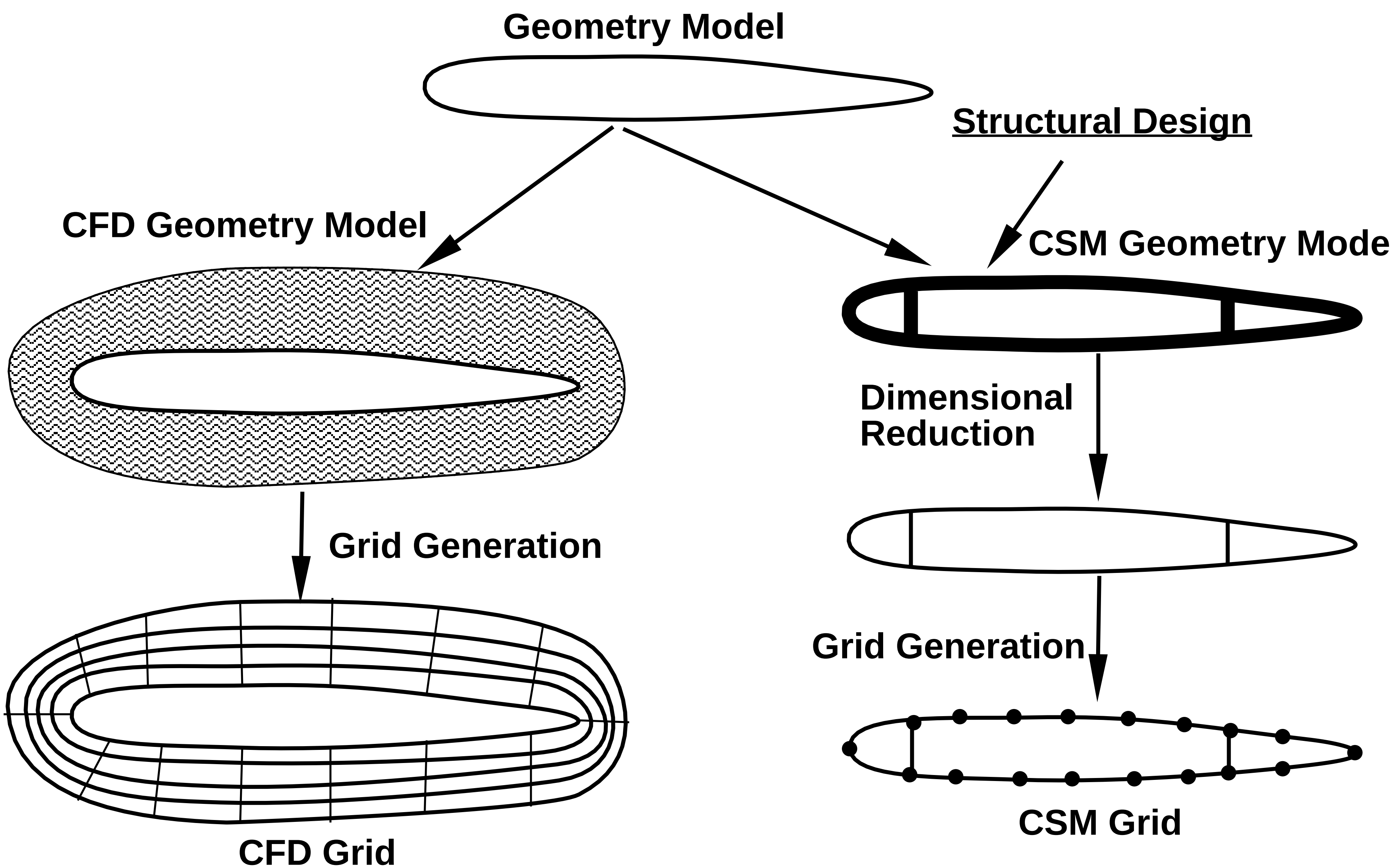
Feature−Based CAD
(Popularized by Sam Geisberg, founder of PTC)

- Is based on Constructive Solid Geometry (CSG).
- Consists of a set of Boolean operations of simple primitives.
- Design is dimension driven based on a parametric solids.
- Design changes are not time consuming.
- Relies on a simple top−down high−level geometry constructions.
- Finished design has features, design intent and multiple−level structure.
- Is ideal for optimization.
- Features can be suppressed for analysis.
- Is not a mature technology yet!

Emerging/Missing CAD Software

- Emerging
  - Preliminary tools are emerging for tolerance modeling.
  - There is some effort to use object technology in CAD
    - Part Library (e.g. Pro/Engine, AutoCAD library of 200,000 parts)
    - Object Linking & Embedding (OLE) from Microsoft
  - Preliminary tools are developed to automatically detect features from physical models (reverse engineering).
  - Virtual environment for CAD will accelerate the design process.
- Missing
  - Robust solid modeling requires a tolerance free geometry representation.
  - Tools to calculate analytical sensitivity based on CAD models.
  - CAD tools to model the interdisciplinary interactions.
  - Automatic tools to idealize geometry models (remove & create geometry).

Grid Generation
(MDO)



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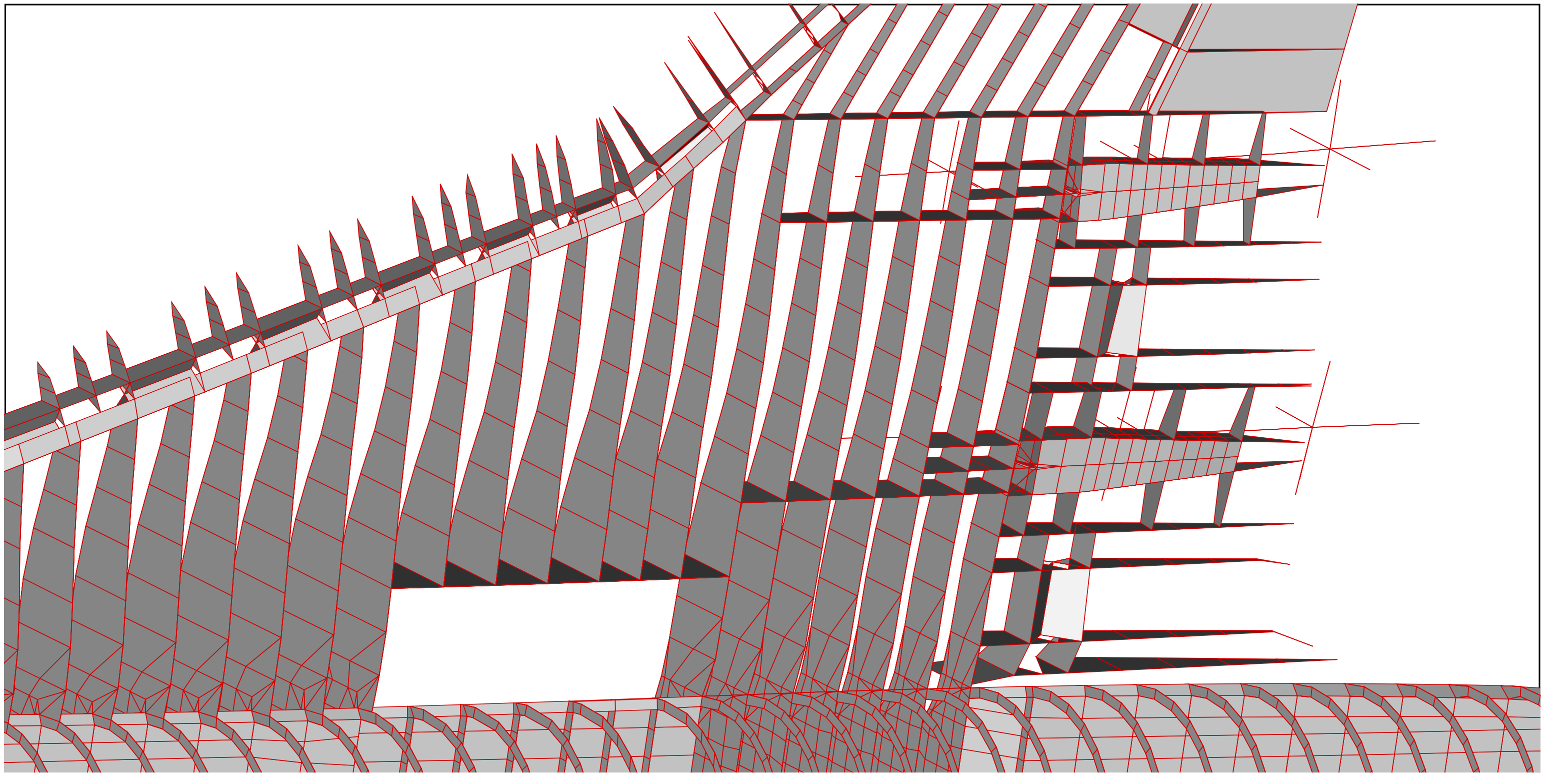
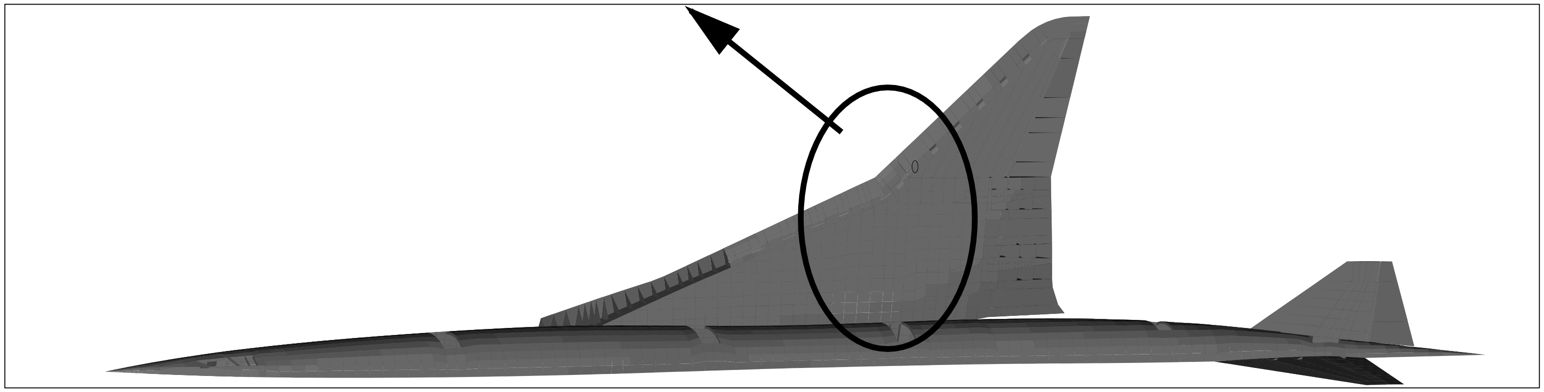
Grid Generation
(FEM Topology)





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Status of Grid Generation

- CAD to grid is still a major bottleneck.
- It takes too many manhours and calendar time.
- It requires a grid specialist.
- It limits the use of analysis codes in preliminary design.

Requirements for Grid Generation Systems
(for a Design and Optimization Environment)

- It must:
  - use CAD generated geometry,
  - handle many surfaces (O(10,000)),
  - handle surfaces with bad parameterization,
  - handle complex geometry,
  - be fully automatic ("push button"),
  - be designed for non−specialists,
  - have a short design cycle time and robust,
  - have capablilies to calculate grid sensitivity.

- It should be able to create boundary layer/stretched grids.

- There should be some level of grid quality control.

- It should operate within an integrated system.

FEM Grid Generation

- o Solid elements (tetrahedrals, pentahedra, hexahedra)

    - o P−elements development at IBM Almaden Research center
    - o Rasna, ProMechanica
    - o PolyFEM (CATIA, SolidWork, COSMOS)
    - o Algor

- o Dimensional reduction of solid models to equivalent solid/shell/beam models.

    - o Medial axis transform is used to reduce a 2D to an equivalent 1D beam.

    - o Tools are not fully automated to reduce a 3D solid model to an equivalent solid/shell/beam model.

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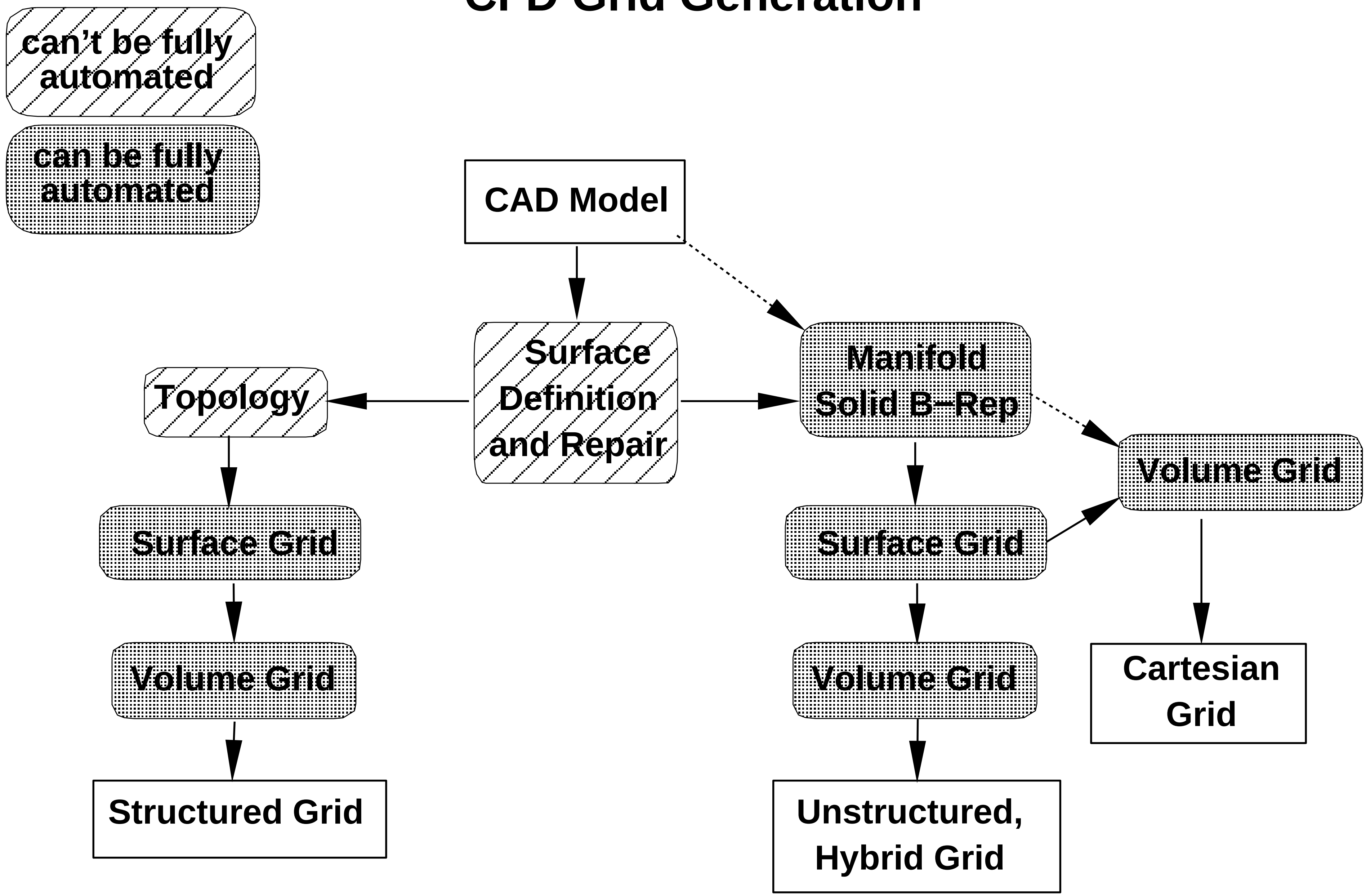
CFD Grid Generation



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GridTool/TetrUSS

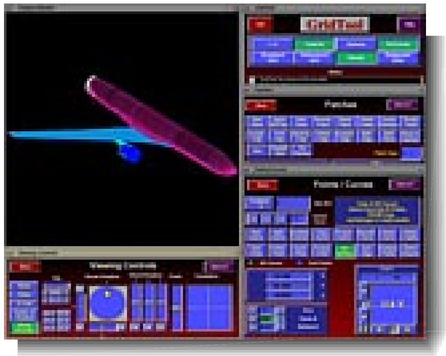
(Integrated Environment for unstructured CFD, 1995)
(1996 NASA Software of the Year)

- Used IGES to deal with large number of CAD systems
- Used NURBS to deal with large number different representations
- Used shrink wrap to deal with large number of small surfaces and surfaces with bad parametrization
- Used surface parameters to deal with local changes
- Used GUI to build a manifold solid B−Rep
- Used loosely coupled integrated system (TetrUSS)*

*** Tom Curry 1996, MacNeal−Schwendler, "We see the need for stand−alone finite−element products diminishing in favor of more comprehensive computer engineering solution."**

What is TetrUSS?

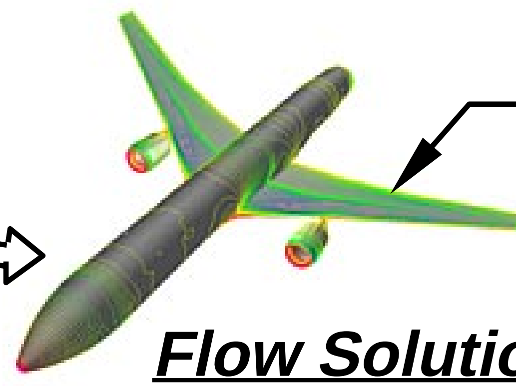
Tetrahedral Unstructured Software System



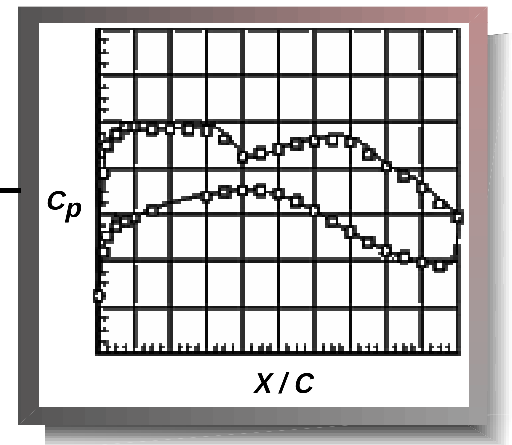
Geometry Setup
- GridTool
- (MSC Patran)

- Modular
- Rapid & easy to use
- Euler & Navier−Stokes
- Interactive BL
- Propulsion effects

Grid Generation
- VGRID
- (FELISA)



Flow Solution
- USM3D
- (FUN3D)
- (AIRPLANE)

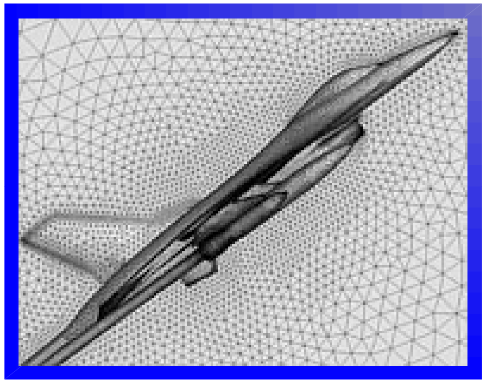


Analysis
- VPLOT3D
- (FAST)

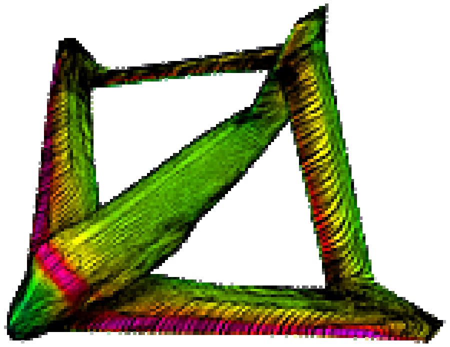
Breadth of TetrUSS Applications

Transports

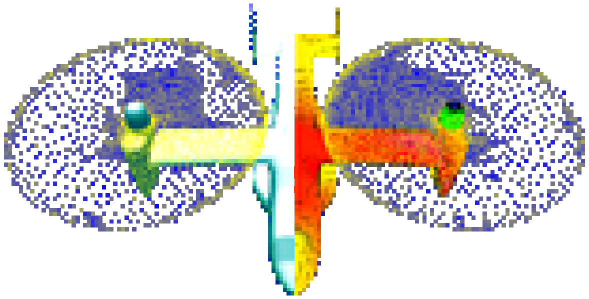
Fighters



Unconventional Aircraft

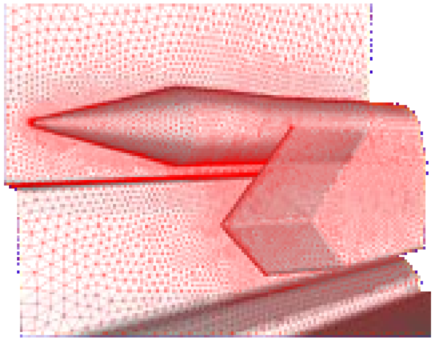


Rotorcraft

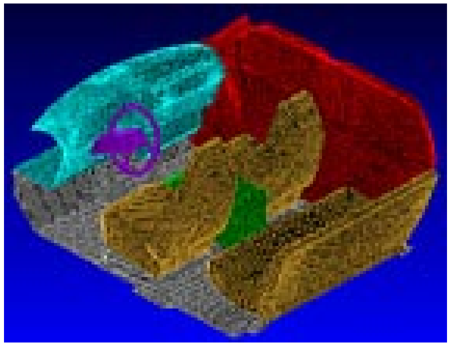


Turbomachinery

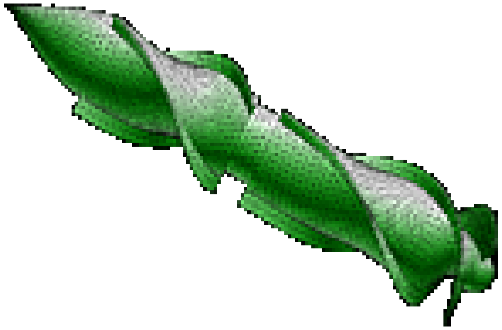
Projectiles



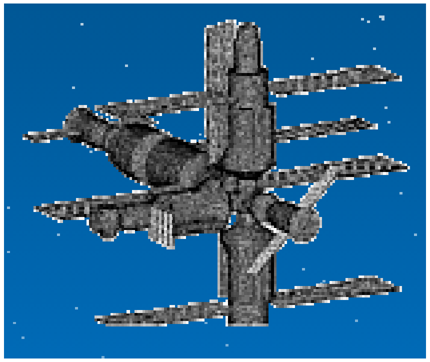
Car Interior



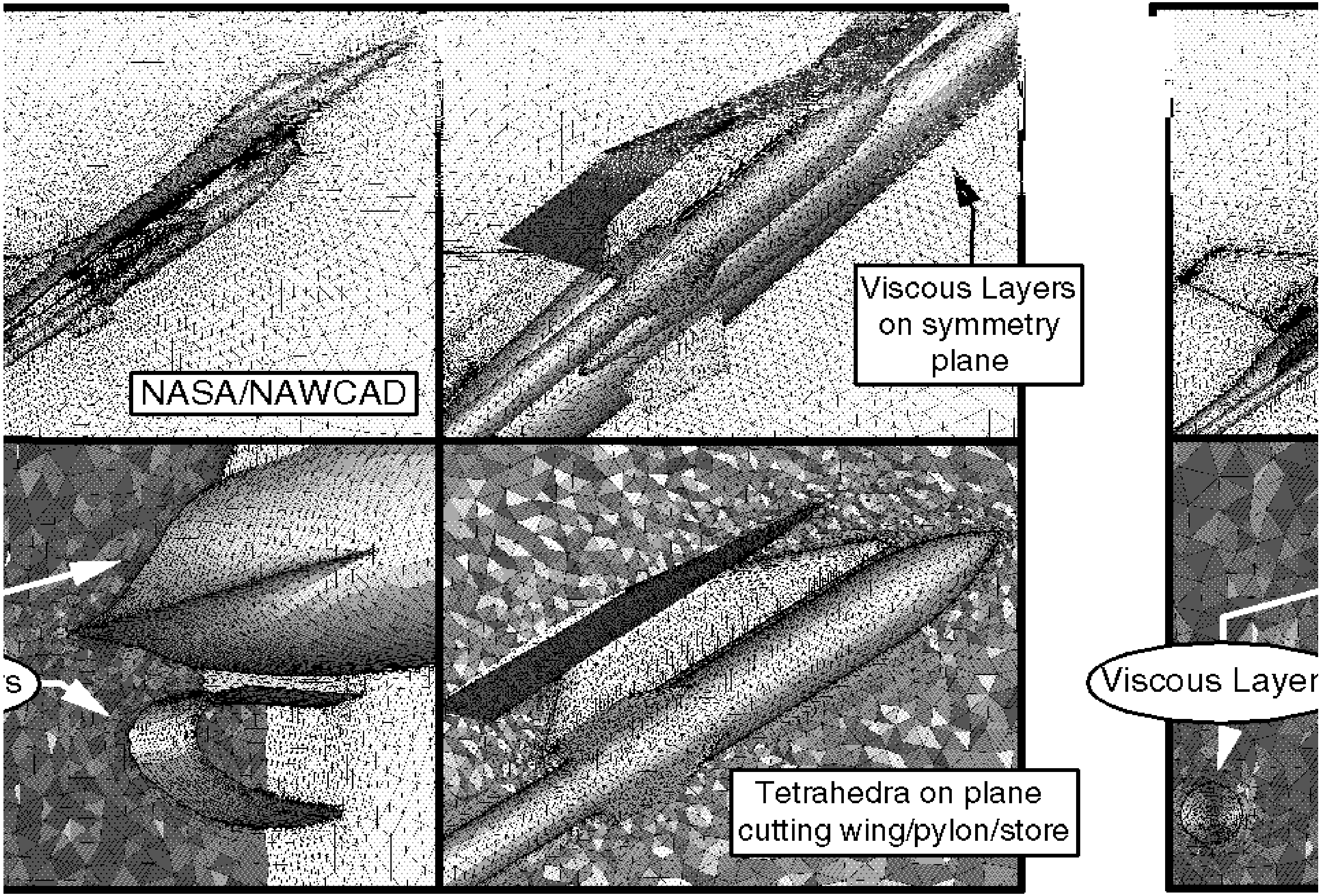
Heart Pump



MIR Station



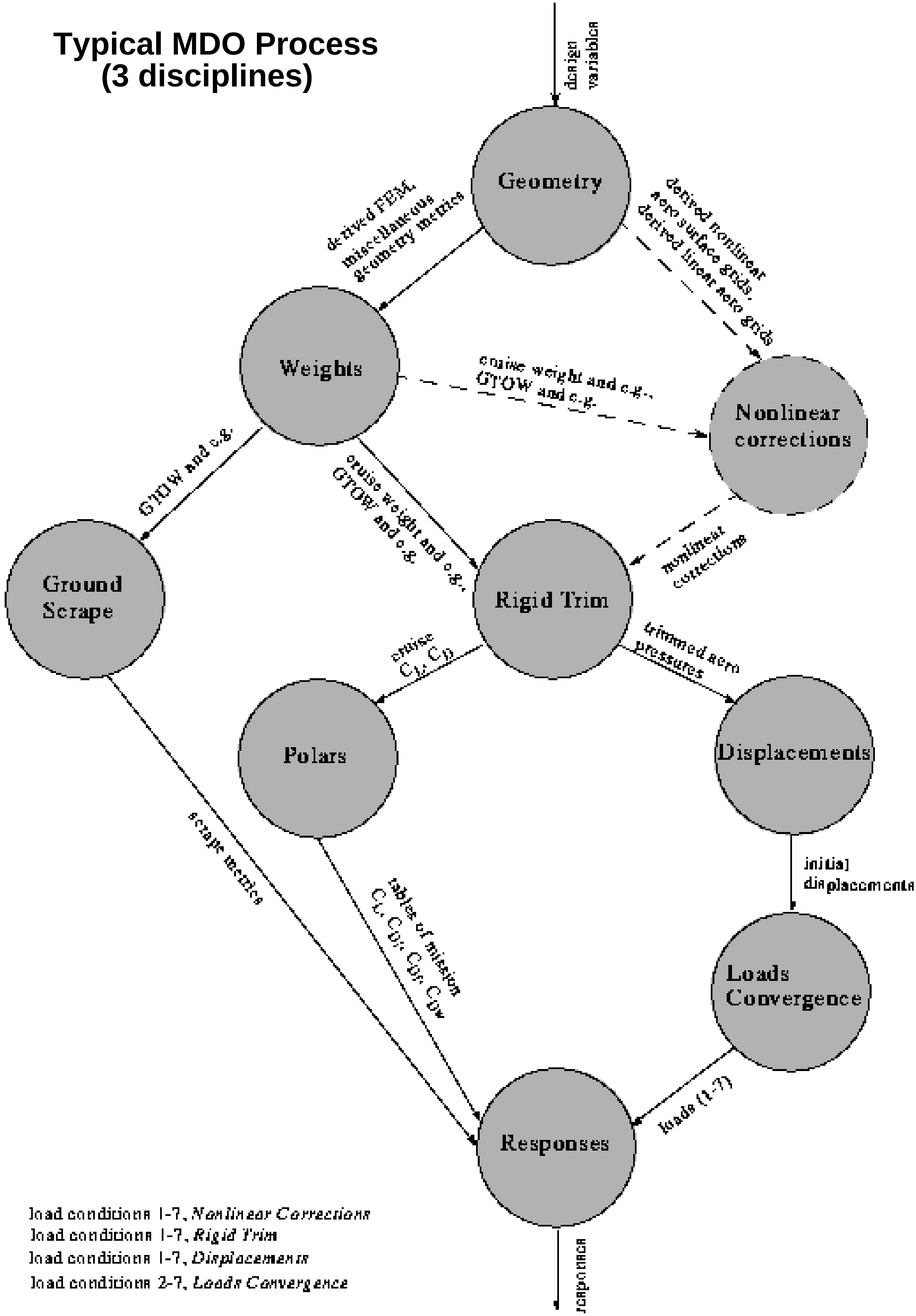
Viscous Grid on a F-16 Configuration



Emerging/Missing Grid Generation Software

- o Emerging
  - o FEM integrated grid generation systems (e.g. ProMECHANICA (PTC), InCheck (MSC), DesignSpace (Ansys) , ...).
    They require no or little FEM experience, and they act like a spelling checkers for engineers.
  - o Integrated CAD, structured, unstructured and hybrid grids (ICEM−CFD)
  - o Advanced unstructured CFD grid generation
  - o Grid generation for design and optimization (CSCMDO)
  - o Automation of surface and volume grid generation (AZ3000)
- o Missing
  - o Rule/knowledge based systems to design CSM topology.
  - o Dimensional reduction of solid models to solid/shell/beam elements.
  - o Feature−based grid generation using Constructive Solid Geometry (CSG)
    High−level features −> high−level grids
  - o Fully automatic topology creation for structured grid

Typical MDO Process
(3 disciplines)



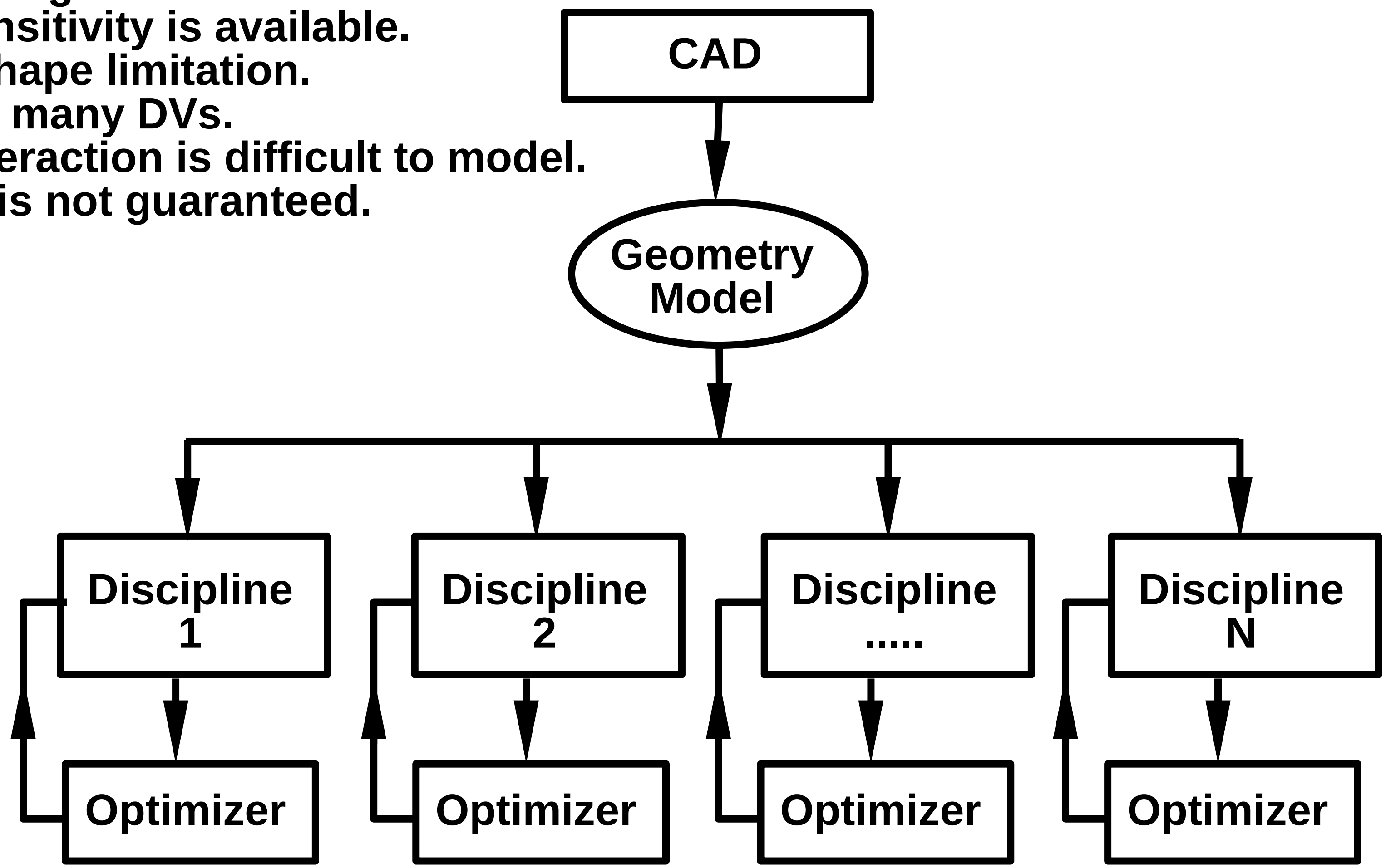
Required Capabilities for Design and Optimization

The system must:

- o Use CAD for geometry creation
- o Generate grids automatically (black−box grid generation system)
- o Use a common geometry representation for all disciplines
- o Calculate analytical grid and geometry sensitivities
- o Transfer data among disciplines consistently (e.g. aeroelastic deflection)
- o Operate in an integrated system
- o Parameterize discipline models consistently

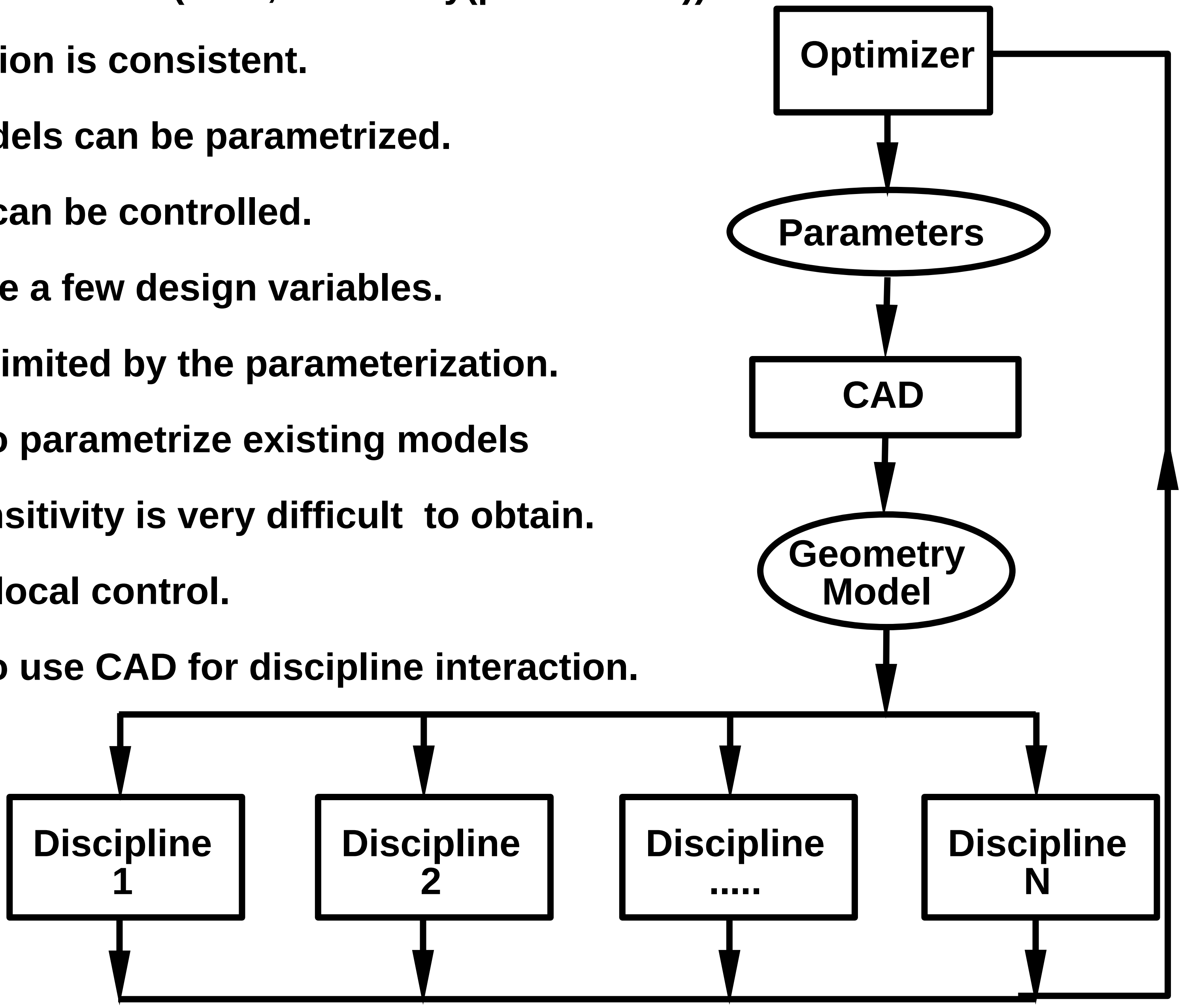
Parameterization Techniques
(Discrete, Grid(parameters))

- o Complex and existing models can be parameterized.
- o Parameterization is inconsistent.
- o There is a strong local control.
- o Analytical sensitivity is available.
- o There is no shape limitation.
- o There are too many DVs.
- o Discipline interaction is difficult to model.
- o Smoothness is not guaranteed.



Parameterization Techniques
(CAD, Geometry(parameters))

- Parameterization is consistent.
- Complex models can be parametrized.
- Smoothness can be controlled.
- Models require a few design variables.
- The shape is limited by the parameterization.
- It is difficult to parametrize existing models
- Analytical sensitivity is very difficult to obtain.
- There is little local control.
- It is difficult to use CAD for discipline interaction.



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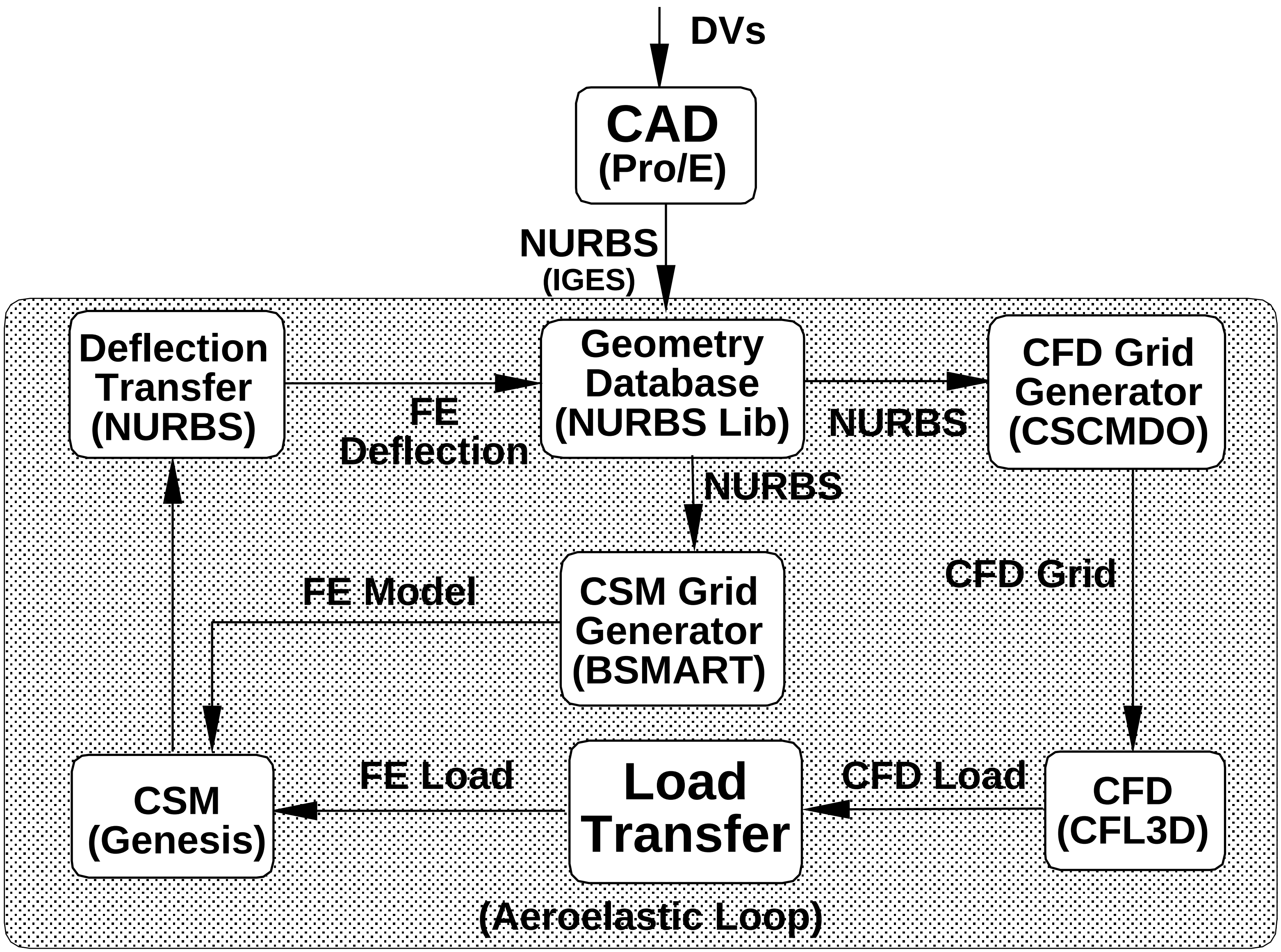
Parameterization Techniques
(HPCCP Process)



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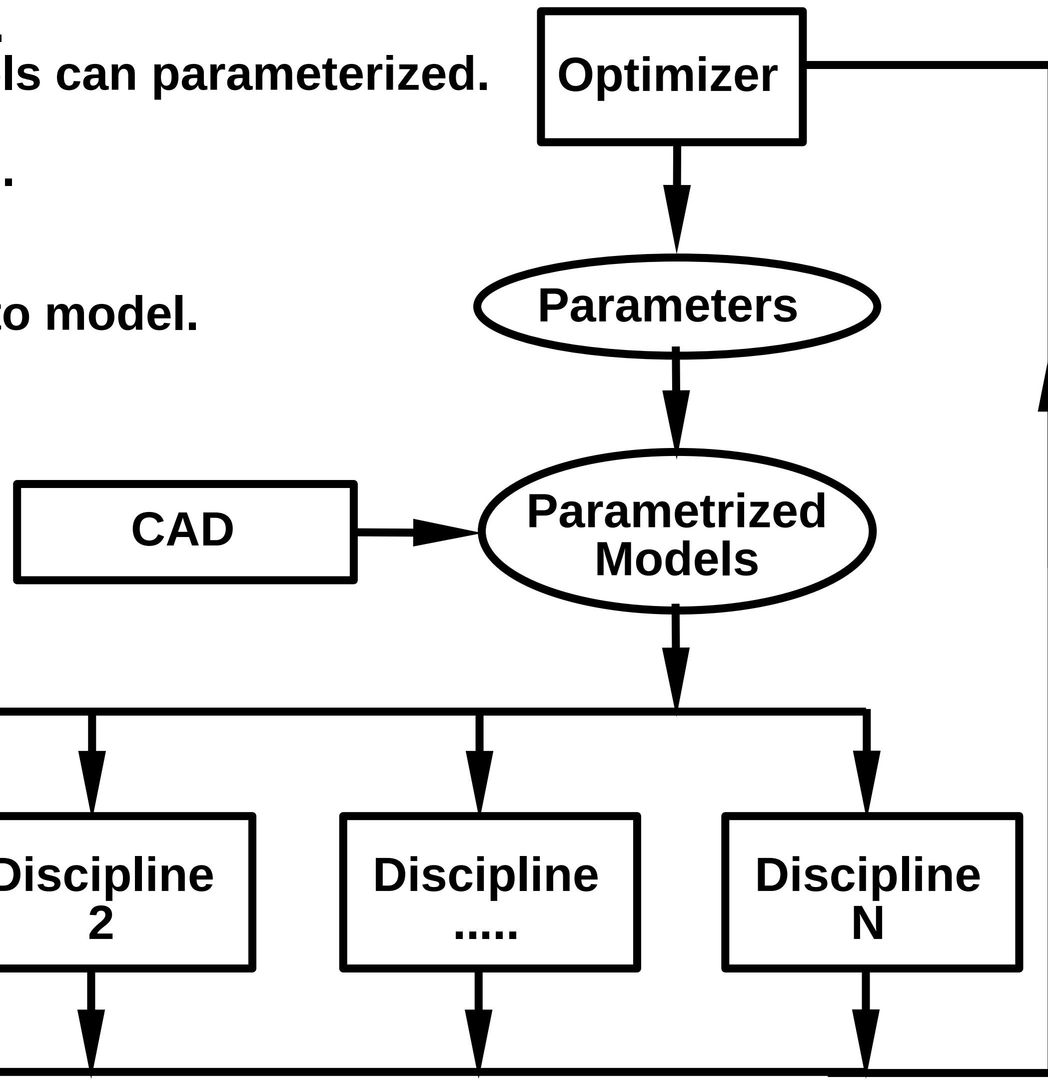
Parameterization Techniques
(Free−Form Deformation, ΔG(parameters))

- o Parameterization is consistent ($G = G_{initial} + \Delta G$).
- o Analytical sensitivity is available.
- o Complex existing analysis models can parameterized.
- o Smoothness can be controlled.
- o It requires a few design variables.
- o Shape changes are limited.
- o There is a good local control.
- o Discipline interaction is difficult to model.



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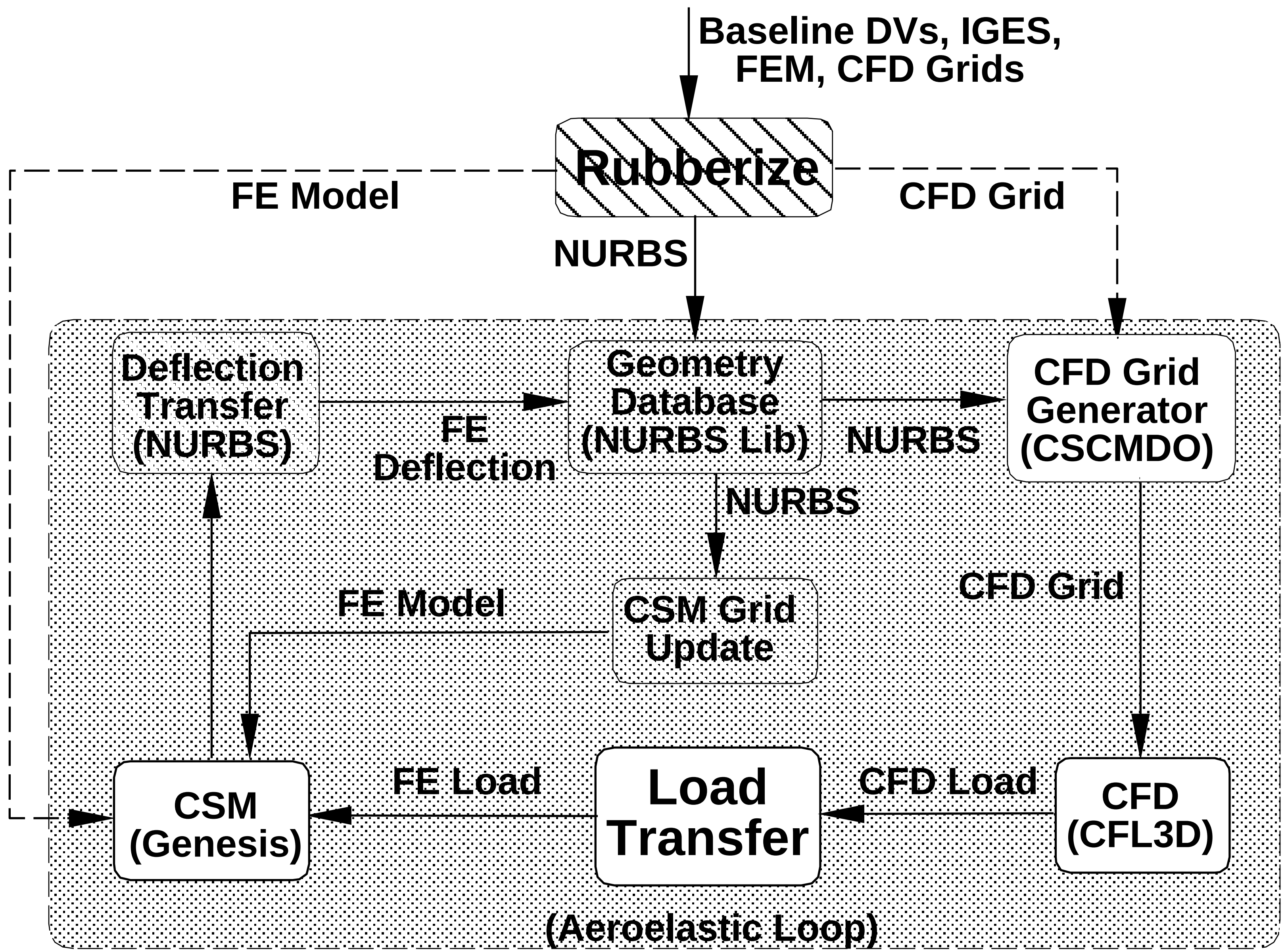
Parameterization Techniques
(Free−Form Deformation, HPCCP Process)



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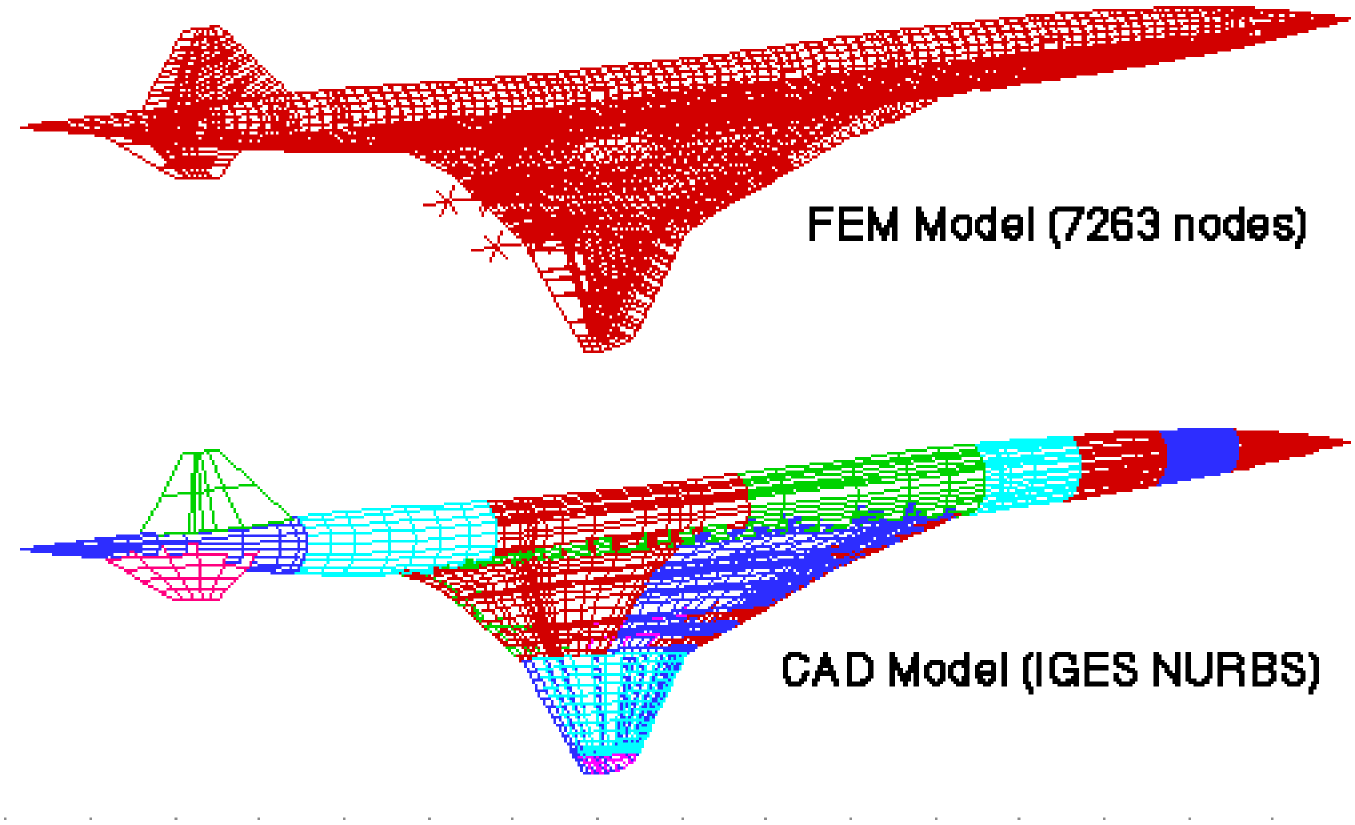
Free−Form Deformation
(High−Speed Civil Transport)



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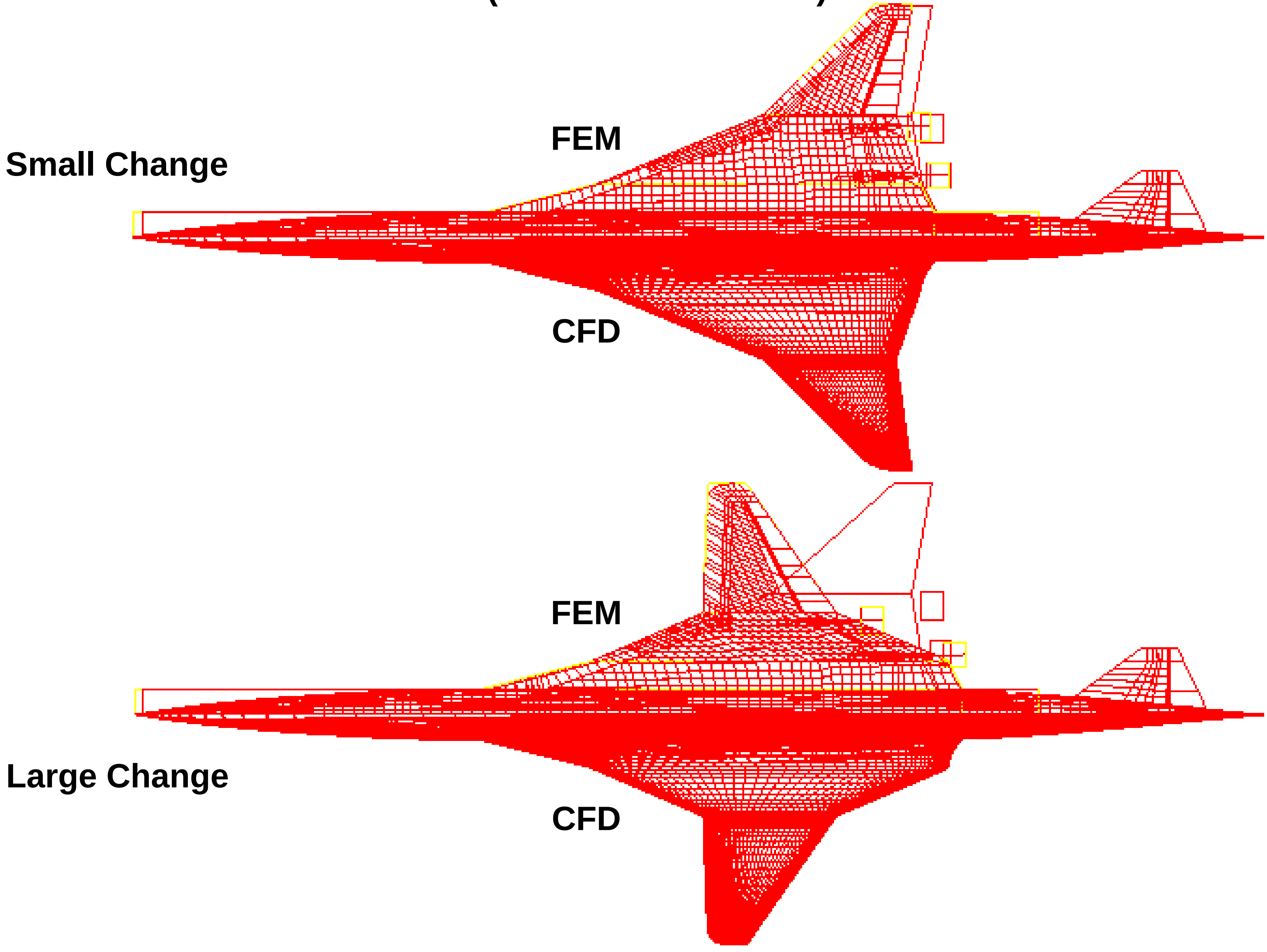
Free−Form Deformation
(Planform Variations)



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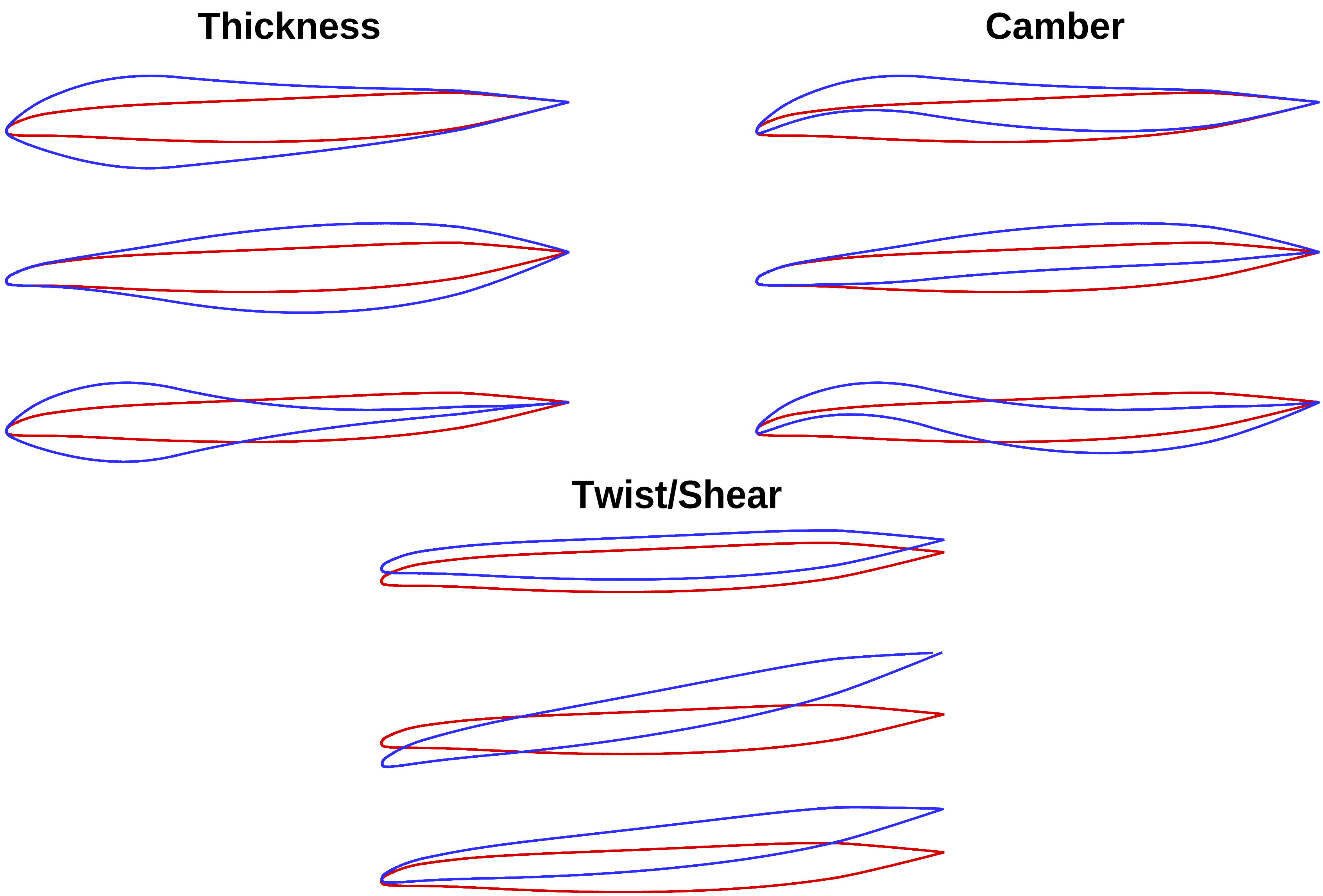
Free−Form Deformation



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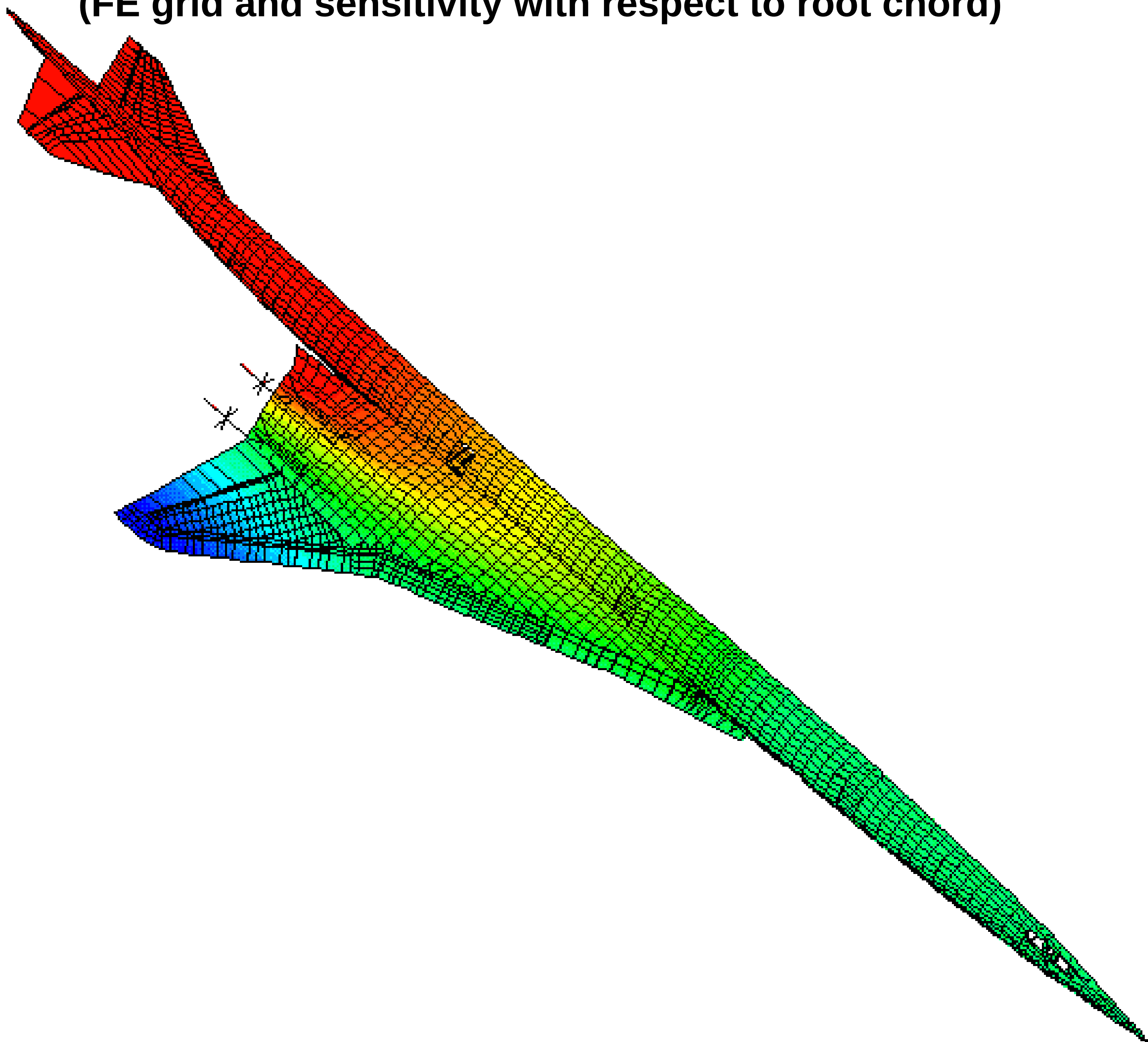
Free−Form Deformation
(FE grid and sensitivity with respect to root chord)



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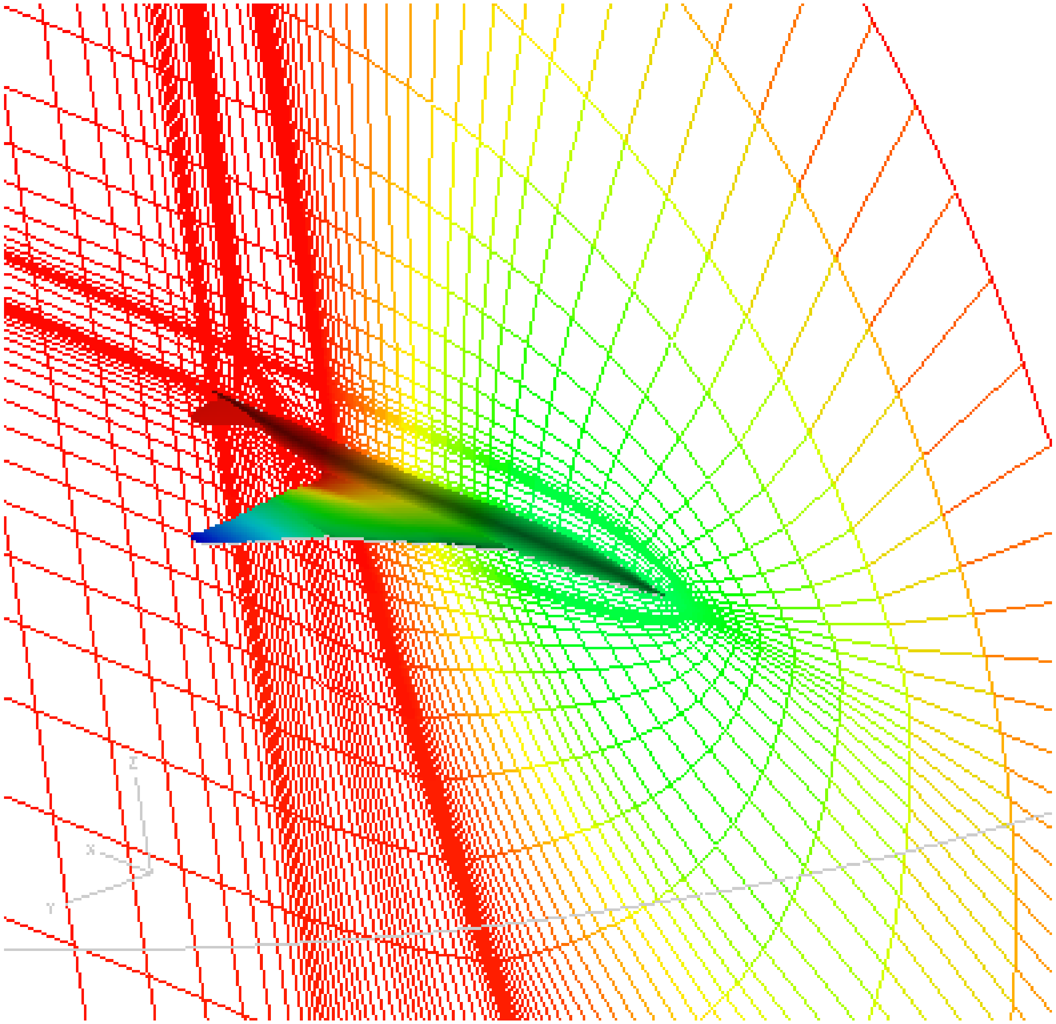
Free−Form Deformation
(CFD volume grid and sensitivity with respect to root chord)



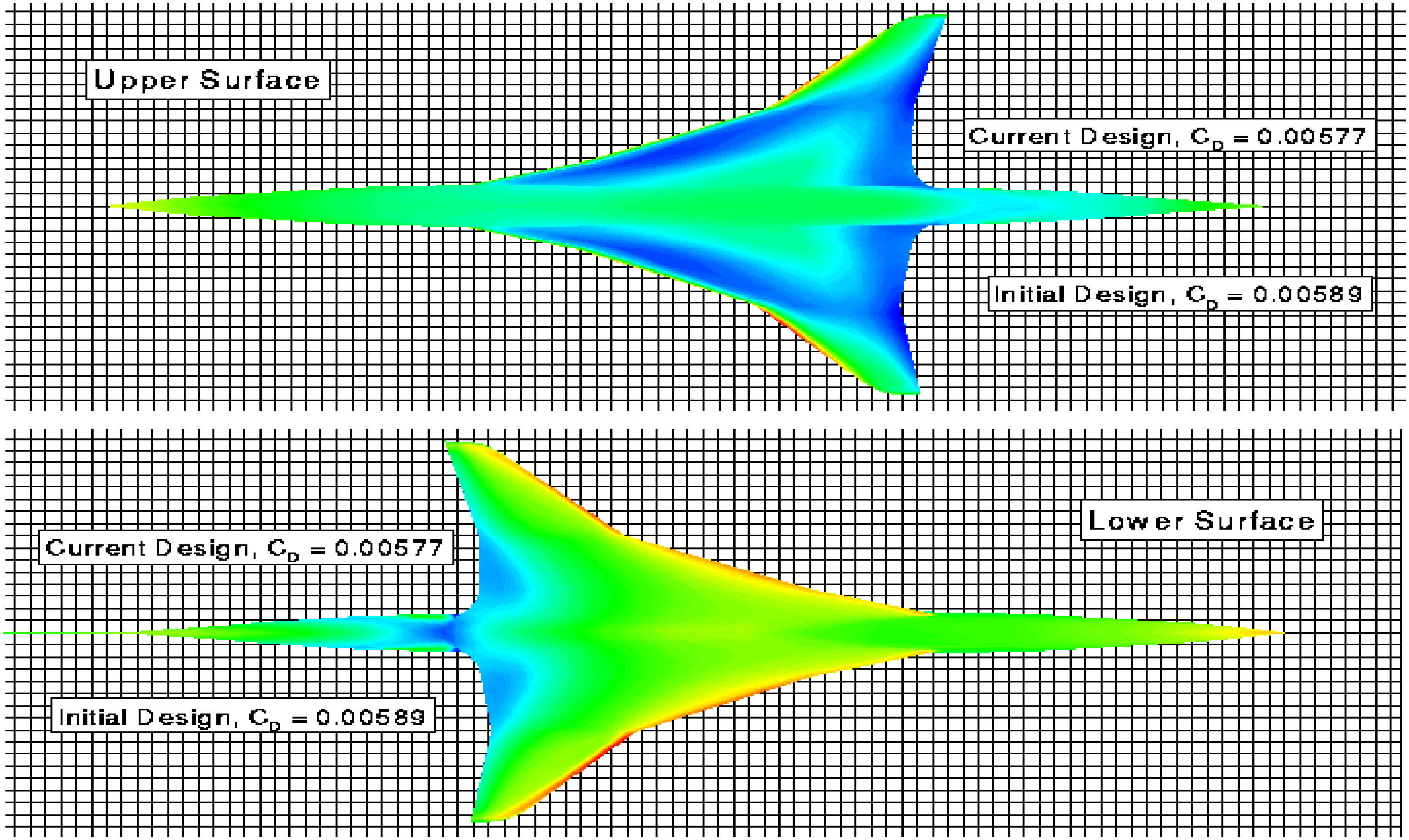
Free−Form Deformation

(CFD solution)

HSCT4.0 AERO OPTIMIZATION (Coarse)

Minimize Drag For Fixed C_L = 0.068768

Surface Pressures



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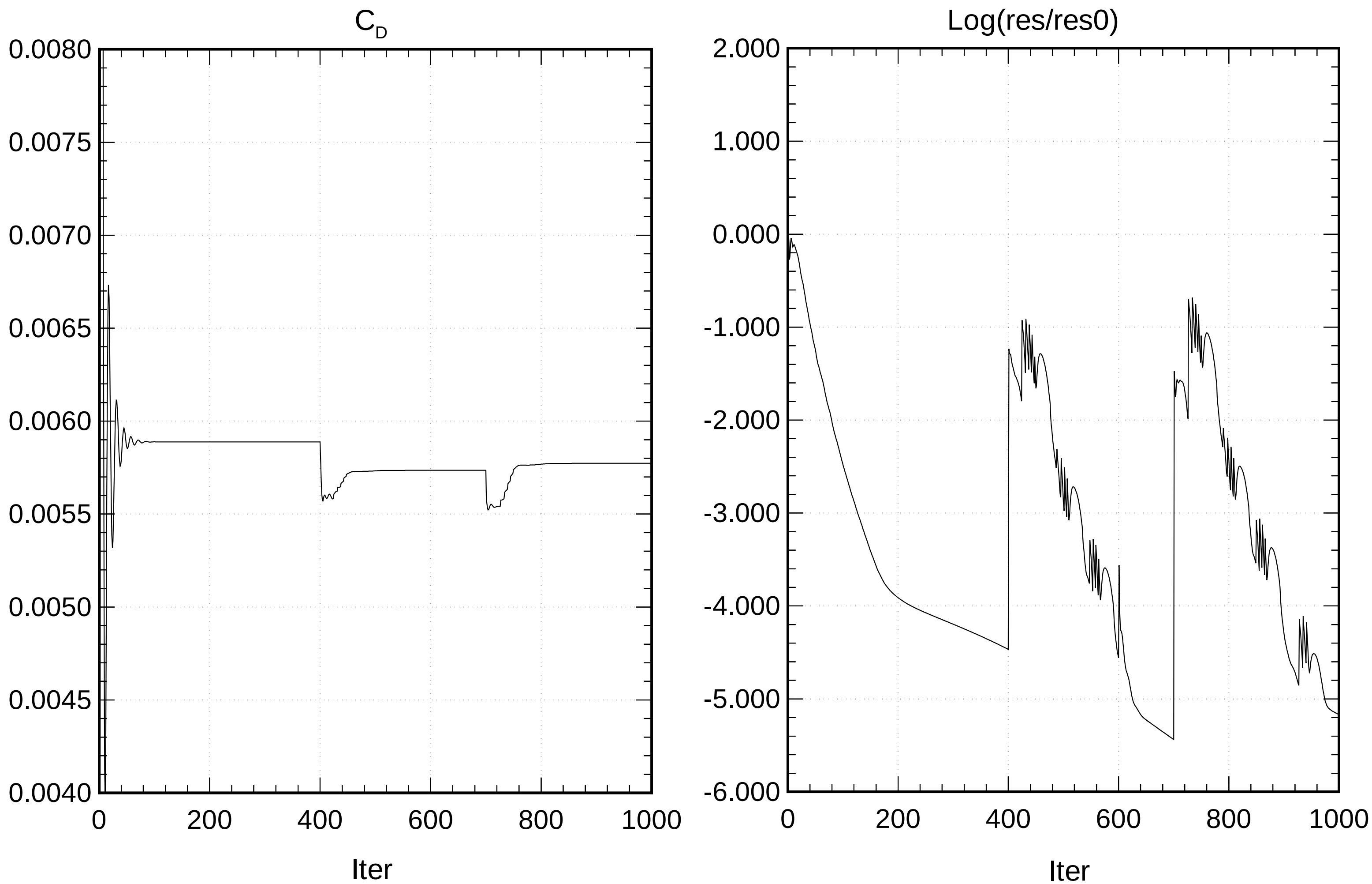
HSCT4.0 AERO OPTIMIZATION (Coarse)

Minimize Drag For Fixed $C_L = 0.068768$

Solution Convergence History



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Emerging/Missing Design and Optimization Software

- Emerging
  - Integrated system approach (e.g. Pro/E, MSC, ...)
  - Computer Aided Optimization (CAO) environment (e.g. iSight)
  - Object oriented design, CORBA
- Missing
  - CAD−based sensitivity analysis
  - High−fidelity integrated multidisciplinary systems for optimization

Research Opportunities

- o Tools to automatically heal/mend solids
- o A tolerance free geometry representation for solid modeling.
- o CAD−based tools for analytical sensitivity.
- o CAD tools to model the interdisciplinary interactions.
- o Automatic tools to idealize geometry models (remove & create geometry).
- o Rule/knowledge based systems to design CSM topology.
- o Dimensional reduction of solid models to solid/shell/beam elements.
- o Feature−based grid generation using Constructive Solid Geometry (CSG)
  High−level features −> high−level grids
- o Fully automatic topology creation for structured grid
- o Tight CAD, grid generation and CAE integration for MDO.
- o Object oriented tools for design and optimization
- o High−fidelity multidisciplinary optimization system

Summary

- o Geometry plays a critical role in MDA & MDO.
- o Parametric CAD must be part of the process.
- o Grid Generation must be fully automatic.
- o Accurate grid generation requires the direct use of CAD data.
- o Multidisciplinary models must be parameterized consistly.
- o Freeform deformation provides a mechanism for parametrizing existing models.
- o Accurate geometry and grid sensitivity are required.
- o An integrated system could shorten the design cycle.